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Architecture for Collaborative Learning Activities in Hybrid Learning Environments

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Abstract: 3D virtual worlds are recognized as collaborative learning environments. However, the underlying technology is not sufficiently mature and the virtual worlds look cartoonish, unlinked to reality. Thus, it is important to enrich them with elements from the real world to enhance student engagement in learning activities. Our approach is to build learning environments where participants can either be in the real world or in its mirror world while sharing the same hybrid space in a collaborative learning experience. This paper focuses on the system architecture and a usability study of a proof-of-concept for these hybrid learning environments. The architecture allows the integration of the real world and its 3D virtual mirror; the exchange and geolocalization of multimodal information, and also the orchestration of learning activities. The results of the usability evaluation show positive engagement effects on participants in the mirror world and, to a lesser extent, on those in the real world.

Keywords: hybrid learning environments, augmented reality, augmented virtuality, mirror worlds, 3D virtual worlds, architecture for virtual learning environments.
Categories: H.4.2, H.4.3, H.5.2, H.5.3, L.2.3

1 Introduction

Information and Communication Technology (ICT) tools have been used to create learning environments that improve student learning. However, the lack of social interaction in web-based environments reduces the motivation of less independent students [Salmon, 00]. A compromise solution is to deploy hybrid or blended environments to obtain the advantages of the technology affordances while retaining the benefits of face-to-face teaching [Oliver, 05], [Graham, 05].

A technological evolution of flat-web, 3D virtual worlds (3DVWs) have improved online learning by fostering student motivation through these immersion capabilities and by providing collaborative learning environments [Chittaro, 07], [Dalgarno, 10]. However, 3DVW graphics are unappealing and it is not easy to fill these worlds with complete and meaningful information. This suggests that just as with the flat web, 3DVW capabilities as learning environments could be enhanced by connecting them with face-to-face learning environments.

This paper focuses on the system architecture and usability study of a proof-of-concept of hybrid learning environments. The architecture allows the integration of the two extreme components of Milgram's continuum [Milgram, 94] as well as two other components of Milgram's: augmented reality (i.e., the superimposition of virtual objects and information on the physical world) and augmented virtuality (i.e., the introduction of elements from the physical world into a virtual one). The virtual and real worlds were merged through mobile technology's geolocation capabilities. A hybrid learning environment was built and deployed using the proposed architecture and a usability study was carried out to explore student perception of it as an immersive and collaborative learning environment.

This article starts with a review of mixed reality applications deployed over single and hybrid spaces along with their architectural implications (see Section 2). Then, we extend the architecture outlined in a previous work [Ibanez, 11] to support collaborative hybrid learning environments composed of the real world and its mirror (see Section 3). A learning activity deployed over the architecture is presented in Section 4. Finally, Section 5 presents the conclusions and future work.

2 Related work

Mixed reality research aims to integrate real world objects into a 3D virtual space generated by a computer. Mixed reality was defined by P. Milgram and F. Kishino [Milgram, 94] as "...anywhere between the extrema of the virtuality continuum" where the real world is located at one end of the line while that the virtual reality (VR) is at the opposite end. Moving from left to right increases the virtual content as the connection with reality becomes weaker. The virtuality continuum also includes augmented reality (AR) and augmented virtuality (AV). In the following, we present an overview of relevant applications in these spaces and their main architectural requirements.

2.1 Augmented reality applications and their architectural requirements

There are mobile applications based on augmented reality in areas such as navigation and path-finding; collaborative assembly and design; industrial maintenance and inspection; cultural heritage; edutainment and games [Papagiannakis, 07], [Elmqvist, 06], [Henrysson, 05], [Stork, 06], [Papagiannakis, 08]. The automotive firm BMW, for instance, uses an AR system to improve the work of its mechanics by means of superimposing virtually animated components over the physical components of the car undergoing repairs [Platonov, 06].

Architecturally, AR systems include mechanisms to track information about user location and the position of real world objects of interest; hardware and software to process information, and devices to show the user the digital information integrated in the real environment [Azuma, 97], [Azuma, 01], [Carmigniani, 10]. Display and tracking mechanisms contribute to physical immersion by showing changes in the environment as a result of movement or interaction.

AR technology naturally supports one of the three types of interaction needed in learning stated by M. Moore [Moore, 89]: learner-content interaction. The quality of interaction supported by an AR system goes from the one achieved by simple WIMP interfaces (windows, icons, menus, and pointing) to what haptic devices offer. [Carmigniani, 10] [Krevelen, 10]. Although earlier AR systems provide limited interaction capabilities, they are broadly used due to wide availability in low cost devices. An educator's main challenge is how to exploit the immersive and interactive capabilities of AR systems to foster motivation, to promote kinesthetic learning tasks and to support cognitive memory processes [Chien, 0], [Dunleavy, 09]. There are indeed some initial attempts to use AR for learning tasks with simple devices such as fiducial markers, PCs, or webcams since they could possibly be acquired by schools due to their low cost. Although these simple devices offer limited capabilities of interaction and immersion, pilot studies have proven them to be effective in fostering motivation, spatial ability and memorization in experiential learning environments [Martin, 10], [Maier, 09], [Chien, 10], [Sumadio, 10].

2.2 Virtual reality applications and their architectural requirements

Although less explored, AV is also present in some promising projects at the Massachusetts Institute of Technology [Lifton, 09]. The Shadow Lab project feeds the virtual world with information from sensors in the physical world, while the Ubiquitous Sensor Portal project displays, in the virtual environment, the presence of people in the physical one. It is also possible to find examples of AV environments in architectural design [Wang, 07], 3D videoconferencing systems [Regenbrecht, 04], and scientific data centers [Clarke, 03]. Finally, VR has been used mainly in 3D simulation, public events organization and collaboration [Dalgarno, 10], [Livingstone, 08].

Augmented virtuality environments are embedded in 3DVWs whose architecture can be peer-to-peer (P2P) or client-server [Lopes, 11]. These are naturally federated systems that have one serious drawback. Namely, the latency and inefficiency of object-search operations for very large numbers of participants can limit their performance/scalability. Croquet [Reed, 05] and Unity 3D Basics [Unity Technologies, n.d.] are examples of these P2P systems. In client-server architectures for 3DVWs, the clients are viewers connected to one or more servers that contain content and provide services [Thompson, 11]. Second Life [Linden Research Inc, n.d.], Open Simulator [OpenSim, n.d.] and Open Wonderland [Open Wonderland Foundation, n.d.] are among the most well-known client-server 3DVWs. Client-server architectures support persistent virtual environments and provide more options for scalability because their server side can be replaced by a cluster of servers and appropriate bandwidth for adequate service quality [Lopes, 11]. Representational fidelity, immediacy of control and presence are considered the basic capabilities of 3DVWs which foster learning benefits [Chitaro, 07], [Dalgarno, 10]. These capabilities could influence motivation, identity construction, the sense of presence and co-presence which, in turn, will produce learning benefits such as spatial knowledge representation, reflective thinking, experiential learning, contextual learning and collaborative learning [Dalgarno, 10], [Dickey, 05], [Lee, 10].

Virtual learning environments can also combine two or more of Milgram's continuum realities into a unique space. In the following, we categorize these approaches in terms of migrating or sharing real or virtual elements.

2.3 Migrating 3d objects across spaces

Objects can be present either in the real or a virtual world but not at the same time. Participants have the illusion of 3D objects that can cross over spaces. Virtual space can be seen as the continuation of the real one and vice versa. For instance, D. Robert et al. [Robert, 11] present a hybrid tangible augmented reality game play space and human-robot interaction area where a robot plays with its virtual peers by passing a graphic object back and forth through an integrated physical and virtual environment. The close coupling of the simulated world's physical laws with material reality maintains a perceptual continuity between the virtual and the real world. Architecturally, such a system requires a mechanical device that can be controlled in the real world, a graphic engine, a hardware device to control the object and "a super physics model ... to coordinate and pair the physics of the real with its simplified virtual counterpart" [Robert, 11]. Expected benefits for learning include increased student engagement in learning tasks and possibilities to apply learning theories such as situated learning and experiential learning to instructional design.

2.4 Migrating participants across spaces

Participants in the mixed reality experience may live naturally within one space and cross the barrier dividing the real and virtual worlds. Typically a user acts through his/her avatar in 3D virtual worlds, but some 3D virtual worlds are being used to carry out experiences where different realities are mixed. For example, the SLARiPS project [Stadon, 09] allows avatars to cross the barrier between physical and virtual space. SLARiPS is deployed in Second Life, requires a marker placed on the floor of the real world and the user must wear a head-mounted display. An XML RPC module was developed, using PHP to communicate between the two worlds. The main goal of the project is to achieve online social engagement in 3D environments, which could be an important learning benefit. The main implication for the architecture is to allow a smooth optical transition of participants across spaces.

2.5 Sharing 3D objects

Participants in both spaces can share 3D objects once a physical-digital link is established between the real object and its representation in the virtual world. Any action carried out on the real object is transmitted to its virtual representation; eventually, actuators will be responsible for moving or controlling the real object. Project MiRTLE [Callaghan, 08] is a Mixed Reality and Learning Environment built using the Open Wonderland platform. The authors create a virtual classroom where teachers and students participate in mixed and online classes.

A lecturer sees and interacts with a mix of students who are present in the real world or the virtual world. She will see students in the virtual world through a large display screen mounted at the back of the room. A camera placed in the rear of the room, and a microphone located in the center of the room provides a live audio and video stream of the lecture to the virtual world.

Students in the virtual world see a live video of the lecture. Open Wonderland's shared application capabilities [Kaplan, 11] are used to foster collaboration among students attending classes in either of the worlds.

The research hypothesis of the MiRTLE Project is whether "avatar representation of teachers and students will help to create a sense of shared presence, engendering a sense of community and improving student engagement in online lessons" [Callaghan, 08].

Sharing 3D objects between worlds involves establishing the objects' representational correspondence along with the implementation of mechanisms to allow collaborative interaction with the objects in any of the spaces.

2.6 Sharing spaces (mirror worlds)

Mirror worlds are informational-enhanced virtual models or reflections of the physical world. The terminology "mirror world" emphasizes the 1:1 correspondence with or "reflection" of the real world. [Murphy, 11]. S. Uusitalo et al. [Uisitalo, 09] developed a social media sharing service that records the position and orientation of media and uses this metadata to show this digital information in a mirror world where spatial relationships are preserved. Their system presents structured content, originating from popular photo sharing services, as a spatial representation. This typical mirror world architecture consists of three main entities, namely the mobile client, the backend infrastructure and the Web UI client. The mobile client records the necessary sensor parameters to represent the captured content in the 3D-space. These sensor parameters include GPS location, and yaw, roll and pitch angles. The backend infrastructure is responsible for accepting the uploading content, storing it and making it available for the Web UI client. The service provided aims to foster the feeling of immersion through spatially structured imagery. The challenge for these architectures is to create a virtual world that users perceive as a valid representation of reality and where events have an impact on both spaces.

In summary, for architectures that enable the migration of digital elements, the critical issue is to show a smooth optical transition of the elements between spaces whereas those that allow assets to be shared require the guarantee of correspondence of the object's state with its mirror.

Despite all the aforementioned efforts, "Virtual world technology is no longer in its infancy, but it's still immature... there is not yet a clear front-runner architecture or implementation that meets the needs of the many potential virtual world applications" [Thompson, 11]. Nonetheless, smart phones are cost affordable and provide different ways of using augmented reality. Few attempts have been made, however, to either fully integrate real and virtual spaces or deploy meaningful learning activities on them that exploit their distinctive features. This work intends to be a step forward toward the integration of a real space and its mirror, which allows the concurrent representation of 3D objects and participants in both spaces.

3 System architecture

The system was designed to support synchronous collaborative learning experiences in an environment that unifies the real world and its mirror. It establishes a one-to-one correspondence between elements of both worlds. Furthermore, it provides mechanisms for exchanging multimodal information across the spaces and supports the workflow of learning activities.

3.1 Design goals

Since the main goal was to create a shared virtual space in which participants could collaborate with one another, a 3D virtual world platform was chosen as the core architecture. An important requirement for the platform was to have extensibility capabilities that could allow both the integration and exchange of information between real and virtual worlds. In terms of performance, a client-server model was preferred to P2P in order to maintain low levels of latency. These requirements were fulfilled by Open Wonderland (OWL), a Java based open source multi-user 3D game platform, based on open standards. It is highly modular and designed with a focus on extensibility [Kaplan, 11].

To meet our learning requirements, the system must provide technical support to current pedagogical theories that encourage active learning. To this end, the system was designed to support two learning strategies based on constructivist theories: situated learning and cooperative/collaborative learning. To facilitate situated learning strategies that could be carried out both in real and virtual worlds in a unified way, the decision was made to use mirror worlds. Recreating real settings in a virtual world is possible thanks to the OWL capabilities to import geolocated 3D objects originally created to be included in Google Earth. Geolocation is the necessary link that the proposed architecture requires in order to establish correspondence between the settings of the two words. However, sharing spaces is not enough to support vivid integration of learning activities, and therefore smart phones were chosen for their potential to migrate both multimodal information and participants across spaces. Additionally, they are widely available and affordable.

In order to maximize online social engagement, participants in the real world will see the avatars of the 3DVWs (augmented reality) on their mobile screen and participants in the 3DVWs will see an avatar representing their peers from the real world in the virtual one (augmented virtuality). Thus, a mobile client, backend infrastructure and a Web UI client were necessary and the last two elements had to be embedded in the virtual platform.

3.2 Main modules of the extended architecture

The proposed architecture is comprised of a server that orchestrates the distributed functionality inherent to 3D virtual environments, and a set of clients used to visualize and manipulate 3DVWs. Any change in the objects that populate the world is propagated from server to clients. The OWL server is extended to consider the real world as an additional client, the mobile client. The unified learning environment can be deployed in the architecture; users in the real world participate through their mobile clients whereas users in the mirror world share the same space. The extended server keeps the information on the 3D virtual objects and real objects centralized. It also sends data regarding their location, appearance, and surroundings. The mirror world must geotag a minimum set of benchmark elements to guide correspondence among the real and the virtual clients of the extended Wonderland server.

An Extended Wonderland Client provides the interface to an augmented 3D virtual environment where users, through their avatars, can observe and manipulate objects in the virtual world, visualize the movements of participants of the real world and receive geolocalized information from the real world. Moreover, users in the real-world share the educational experience with their peers through their mobile client. They can see their peers' superposed avatars on their mobile phone screen. Thus, the architecture allows both augmented reality and augmented virtuality. Finally, the architecture supports the transmission of geolocated information.

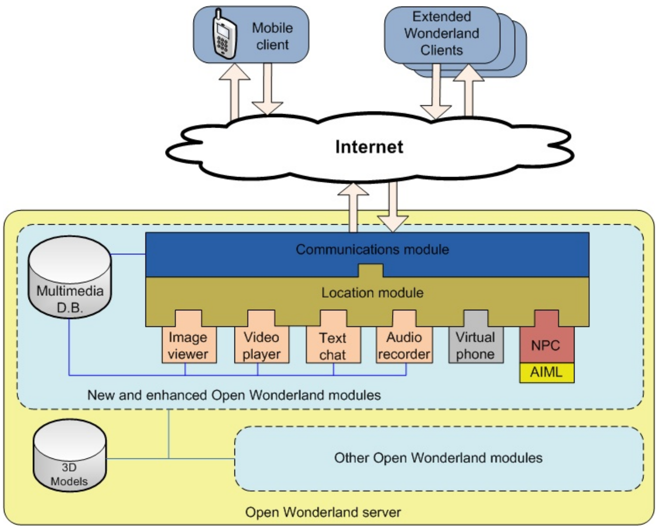

Figure 1: System Architecture

The architecture presented in Figure 1 exploits some of the extensibility possibilities offered by OWL, namely cells, capabilities, plug-ins, custom connections and custom Web applications. In OWL, a cell is a 3D object that can behave as both client and server, react to user input, or send and receive messages from the server. Functionalities that can be applied to any cell are called capabilities. Both cells and capabilities relate to 3D objects that have a particular location in the world. Extensions that are not spatial in nature can be added via plug-ins and will be available to users no matter where they are in the world. A custom connection is a data channel between a set of clients and the server. Finally, custom Web applications let developers add functionality to the Web administration user interface or completely new Web services [Kaplan, 11]. The main extended modules are:

1. Communication Module. The exchange of information between the real and virtual world is through this module which extends the OWL server via a custom connection. The object type [text, audio, video, Non Player

Characters (NPCs), avatar], the position of the objects and their content is sent through a data channel between the clients and the server.

2. Location Module. It allows in-real-time processing of geo-location information about people in the real world and avatars in the mirror world. It is included as a custom connection.
3. Multimedia Modules. They are provided by Open Wonderland and are enhanced with geotagged information in order to allow clients to locate items in a space (virtual or real). These modules use a data base with multimodal information.
4. OWL's Virtual Phone Module. It provides communication capabilities through VoIP protocol.
5. NPC-tutor Module. The orchestration of activities is directed by a narrative process carried out by NPCs that ask participants questions and process their answers via an AIML (Artificial Intelligence Markup Language) engine. The NPC-tutor Module is implemented as a cell. The client reacts to the event: "avatar is approaching" by sending a message to the server. Then the server broadcasts a voice message to a group of clients and the NPC-tutor enacts a dialogue. The AIML engine is added to these kinds of cells as a capability.

This architecture differs from that presented in [Ibanez, 11] in three main aspects. First, this architecture orchestrates learning activities using NPCs instead of an IMS-LD engine. This decision reflects our intention to prioritize object migration between spaces over activity orchestration, and to focus server activity on integrating real and virtual worlds. Additionally, Multimedia and Communication modules have been extended to integrate augmented reality. All of this forced the restructuring of the system as a layered architecture.

3.3 Exchanging information across the worlds

Activities start when a participant from the real world establishes a TCP connection with the platform and sends a "login request" message through her mobile phone. As a result, that mobile phone becomes a new Mobile client and an avatar representing the participant appears in the mirror world. Once the server has augmented the virtual world with the representation of the new client, it sends back the state of the virtual world. The state includes information related to avatars representing other real users and multimedia content. Information regarding all other participants includes their identification, position and distinctive characteristics, such as sex and clothing colors. The multimedia (audio, video, and image) content should have associated its location. The information received can be superposed to the real world by the Mobile client. Thus, as a result of a "login request", the virtual world is augmented with a representative of the mobile user and the new Mobile client receives augmented reality information on her mobile screen. The Open Wonderland server keeps this connection open, to both broadcast any text messages received and periodically broadcast the position of all participants.

All mobile clients in the hybrid reality environment will periodically send their locations (GPS coordinates) to the Open Wonderland server. The server will use these GPS coordinates to update the position of the avatars that represent each Mobile client. Additionally, any Mobile client can send multimedia information to the Open Wonderland server, adding the item's GPS position to the content. Conversely, the

Open Wonderland server periodically sends all clients the state of the world which includes:

- The position and identification of every avatar, including all avatars representing real clients. The Mobile client uses this information for augmented reality.
- The position and type of multimedia content. Any Mobile client may then ask for the actual content of any multimedia file announced by the server.
- The number of virtual phones and their identifiers. This information is useful for establishing VoIP communication with the participants in the virtual world.

Phone calls are started by the Mobile client who calls the virtual phone provided by OWL. Once the connection with the virtual phone is established, the user in the real world and users in the virtual world can maintain a verbal conversation using VoIP technology. It is also possible to have synchronous written communications among all participants. When a Mobile client sends a text message, the server broadcasts that message to all other clients.

4 Case study

The proposed situated learning experience took place on Madrid's Gran Via and its mirror image in a 3DVW. It was designed as a pilot study to evaluate the feasibility of encouraging and improving listening and speaking skills of advanced students of Spanish as a Second Language. To foster engagement, participants had to find all the words that make up a hidden sentence. For each activity completed successfully, they received a new piece of the sentence puzzle.

Students performed the activities through their avatars in the mirror world where they had access to limited information about the shows playing in certain theaters on the boulevard. Meanwhile, instructors were near the chosen theaters, ready to collaborate with students. Instructors compiled information that was not available in the mirror world according to the student requirements. Then instructors sent students back the required multimodal information via telephone. Neither instructors nor students in any group had the complete information, thus they were forced to collaborate in order to achieve the common goal: to complete the sentence puzzle.

Non Player Characters (NPCs) directed the flow of activities by proposing new questions for students, checking for right answers and providing feedback. Students in the virtual world were asked the questions orally by the NPCs who then received and evaluated their written answers. When an answer was correct, participants in both worlds had access to multimodal information that provided them with another piece of the puzzle. When an answer was incorrect, the NPC posed another question.

The learning activities were successfully concluded when the sentence was completed.

4.1 Goals

We conducted a pilot study to determine the participants' perception of usefulness of the hybrid environment as an immersive collaborative learning environment.

4.2 Participants

The participants were twenty volunteers with above average skills in the use of smart phones. However, they had no experience using augmented reality commercial applications or 3D virtual worlds.

4.3 Method and procedure

The usability study was conducted with qualitative research design, think-aloud protocols, interviews and observation during experiments to learn the participants' thoughts, how they interacted with the system and their partners and finally, their response to the use of the hybrid environment for educational purposes [Nielsen, 94]. The study was focused on detecting both facilitators and barriers as elicited from user interaction with the system, and from their observed collaboration with each other by means of the communication tools available. We use the term facilitator for any element that makes it easier for users to carry out the activities and the term barrier for any element that interferes with the users' achievement of their tasks.

Five different sessions were carried out, each with two groups. Each group had one instructor in the real environment and one student in the virtual world. The groups had to work collaboratively to achieve a common goal.

4.4 Measurements

The architecture developed integrates a real environment with its mirror and it was designed to engage virtual world participants in more lively learning activities where users in both worlds can participate. Taking advantage of the architecture, the case study was designed as a situated learning experience where participants had to collaborate to achieve a common goal. Thus, we were interested in observing the extent to which participants in both worlds had the feeling of "being there" and "being together". "Being there" reflects the degree of immersion in the hybrid environment and in the situated learning experience, and thus depends on technical and pedagogical factors. "Being together" reflects the feeling of belonging to a community.

4.5 Results description

We observed that participants in the real world were unsure at the beginning of the tour, but soon gained self-confidence. Collaboration with their partners in the mirror world emerged naturally.

4.5.1 Facilitators identified

During the activities in the learning environment, users had to interact with several different system elements. According to users, a coherent response to their actions by the system contributed greatly to their sense of being an active part of the world.

Students in the mirror world expressed a feeling of being immersed in the learning situation. They perceived it to be very positive to have an NPC representation of their partner in the virtual world and the possibility to follow his/her route. They also found it very positive to receive information in real time. Some of the participants' comments regarding engagement were:

- "I really enjoyed the part when the teleporter appeared after passing the test. It was like treasure hunting!" (Participant in the 3DVW).
- "It is original, positive. The interaction with a real person who is there, in the real place, provides excitement and a desire to keep on playing, learning" (Participant in the 3DVW).

Those who came from outside Madrid reported that it was useful to have a mirror world where the city's cultural activity could be observed. Some participant comments regarding immersion were:

- "I think the visual part is quite accurate. It helps you picture yourself in real life and discover a new city" (Participant in the 3DVW).
- "The Gran Via is well recreated, but there should be more people and more things in it. I know that street and it's always crowded. It's not an empty street" (Participant in the 3DVW).
- "Look! He is just in front of the theater" (Participant in the real world when the avatar appeared on her mobile screen).

Evaluators observed that students collaborated spontaneously with their partners and helped each other whenever difficulties arose:

- "The easiest part is to talk to the other user and use the tools to communicate with him" (Participant in the 3DVW).
- "Collaborating with the other user was very easy and it helped me a lot. If the other user had been another student from my class, I would have talked more" (Participant in the 3DVW).
- "I loved the phone call. It provides reality. It's really good" (Participant from the real world).

The participants highlighted the importance of the recreational aspect within the environment when carrying out the tasks. The activities were enjoyable and that made it easier for the users to complete them. They pointed out the benefits and contributions of this aspect of the experience. The tasks proposed were perceived as a game, which motivated the participants to keep doing more tasks and, ultimately, to keep learning.

4.5.2 Barriers identified

All the barriers, identified both in the real and the virtual world, were related to immersion. In the virtual world participants experienced problems related to representational fidelity whereas participants in the real world had problems recognizing their peers in the virtual world.

In order to achieve a sense of reality in a synthetic world, it is necessary to ensure that the actions that take place can be done in a natural way. This means participants have to be able to carry out the actions without thinking about how to do them and, moreover, technological mediation has to be transparent to them. However, when moving their avatars around the virtual world, at times participants experienced that their avatars went through building walls. This aspect was rated negatively by participants who interpreted it as disturbing and discomforting.

Four out of ten participants located in the real world suffered from technical problems that prevented them from achieving full immersion. The first problem was related to the difficulty in hearing the telephone conversations clearly due to the noise on the boulevard. Participants easily solved this problem by using the chat option. The second problem was due to the superposition of avatars on the mobile screen. When participants in the real world did not visually perceive their partners' presence, they felt partially disconnected. The need to see and hear their partners in order to feel totally immersed was evident.

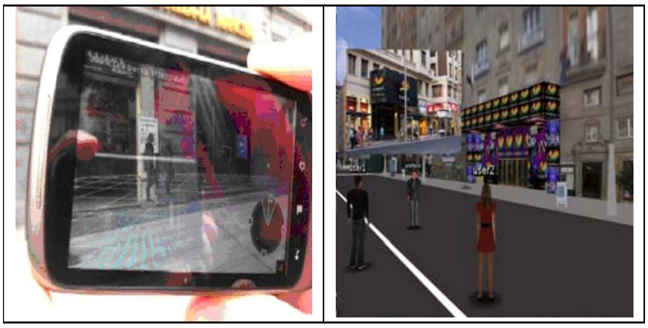

Figure 2: System view for participants in the real world (left) and the mirror world (right)

4.6 Discussion

The use of a mirror world combined with its integration with the real environment was an important motivational factor for participants in the synthetic world. Although participants in the real world could not experience a fully immersive experience, they showed engagement in activities and collaborated actively with their peers in the virtual world. Thus, while the technical problems persist, it is preferable for only instructors to act in the real world.

In spite of these technical problems, participants were completely engaged in the mobile conversation and most of them continued the discussion after the experience had ended, thus we can claim that a learning community was established. Participants always showed their willingness to meet the challenges posed and found it rewarding to discover the hidden words.

5 Conclusions

In this work we have presented the architecture that supports augmented reality and virtual reality by joining the real world to its mirror in a 3DVW. Mirroring the worlds was possible thanks to the geolocation of 3D object models in the 3DVW. The architecture is in charge of keeping participant position updated and sending it to the other world. Exchange of multimodal information was also possible and the actions were orchestrated by NPCs. The system was a successful architectural proof-of-concept that showed the feasibility of enacting hybrid learning environments where multimedia and participants share the same hybrid space.

We conducted an empirical evaluation to determine the usefulness of our hybrid learning environment in terms of motivation, immersion in a situated learning experience, and participation in collaborative activities. We found high levels of participant satisfaction in the 3D virtual world and, to a lesser degree, in the real world.

Now that the usability study of the hybrid learning environments built with our system have proven their motivational and social possibilities, it is time to develop a robust architecture where real courses can be enacted.

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